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Sensitivity of Potatoes to Soil Porosity

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SENSITIVITY OF POTATOES TO SOIL POROSITY

The Difficulty of Maintaining Suitable Tilth in Wooster Silt Loam

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INTRODUCTION

When field experiments were first initiated at Wooster in 1894, one of those started by Thorne was a fertilizer test with potatoes, wheat and clover in a three-year rotation. Of the 10 acres occupied by this experiment, part had been farmed for about 30 years and part was cleared from forest and first cropped to potatoes in 1896. For the first four cycles of the rotation potatoes yielded considerably better on the newly cleared land than on the previously farmed area.

The experiment was not designed as a comparison of old land with virgin soil but the dividing line extended through the center tier of plots and the evidence is clear from the old records. Potato plants died down a week or two earlier on the long-farmed half. Thorne concluded that the old land must be infested with some potato disease.

During the second four cycles of the rotation the yield on the cleared land declined to about the same level as the other. At this time Manns (11) studied the plants dying earliest and found them infected with Fusarium wilt (*F. oxysporum* Schlect). Thereafter his recommendations were followed in obtaining and handling the seed potatoes. After 1922 certified seed was regularly planted and a power sprayer was used to apply fungicides to the growing plants.

The adoption of these measures failed to eliminate the premature dying. The general level of tuber yields on the best fertilized plots remained below the level obtained during the early years on virgin soil, (Table 1).

Test of crop rotations. Similar yields were obtained in crop rotation experiments started by Williams in 1915. These were located on previously-farmed land which, as far as known, had never been cropped

[1]During the course of this study the writer has had helpful advice from several soil technologists. He feels particularly indebted to G. W. Conrey, R. M. Salter and R. E. Yoder.

Since 1946 the studies have been conducted with Federal support as a Purnell Project.

TABLE 1.—Data Illustrating Trend in Yield of Potatoes and of Wheat on a Well Fertilized and on a Manured Plot in Long Continued Experiment

Fertilizer applied to potatoes, 1000 pounds per acre 5-7½-15; manure, 16 tons per acre, without supplementary fertilizer. Data of Thorne (16).

Period	Average annual yields in bushels per acre							
	Potatoes				Wheat			
	Land farmed prior to 1894		Land cleared from forest 1895		Land farmed prior to 1894		Land cleared from forest 1895	
	Fertilized	Manured	Fertilized	Manured	Fertilized	Manured	Fertilized	Manured
1894-05	165	138	249	227	31 5	29.9	47.1	40.4
1906-17	185	216	164	174	37 6	38.4	41.6*	39.5*
1918-32	178	200	171	195	36.4	33.1	46.1	41.0

*Crop failure of wheat in 1912 not included in the average

to potatoes. At the outset the potato yields were low. After the adoption of certified seed and power spraying in 1923, four of the eight rotations averaged somewhat above 200 bushels per acre, (Table 2). The yields, however, were below expectation.

TABLE 2.—Yield of Potatoes in Crop Rotation Experiments Started in 1915

Experiment conducted by C. G. Williams. Data from Special Circular 53, 1938.

Length of rotation years	Crop sequence preceding potatoes	Average annual total yield of potatoes, bushels per acre 1915-20	1921-25	1926-30	1931-35
2	Wheat, with sweet clover	104	114	170	185
3	Wheat, red clover	139	111	214	210
3	Oats, red clover	140	144	197	219
4	Corn, wheat, red clover	146	153	225	223
4	Soybeans, wheat, red clover	136	145	231	211
4	Wheat, red clover, corn	99	105	134	180
5	Wheat, red clover, timothy, corn	92	105	161	164
5	Soybeans, wheat, red clover, corn	110	119	180	173

Insufficient fertility of the soil may well have been a factor limiting the yields. Manure was supplied at the rate of two tons per acre per year of each rotation, all applied prior to plowing the clover sods. In addition, 16 percent superphosphate, at 200 pounds per acre, was applied to each crop of potatoes, corn, soybeans or small grain. Only where the potatoes were grown after clover did the yields rise above 200 bushels per acre. Premature dying of potato plants, however, occurred in all the crop rotations to about the same degree as in the older fertilizer experiment.

At this point it should be emphasized that yields of crops other than potatoes were up to expectation and well maintained in these long continued experiments of Thorne and Williams. In particular, the wheat following potatoes yielded exceptionally well, (some data are included in Table 1).

Further study of the infecting organisms. Planting certified seed potatoes and using power sprayers, a few growers in the state between 1924 and 1928 reported yields of 300 bushels (Tussing, 17). On the other hand, many inquiries were received asking why these measures did not give better yields, and failed to eliminate the vascular browning of the tubers. In the state as a whole, the average yield increased 15 bushels per acre between 1923 and 1930, but it remained below 100 bushels per acre.

In 1924, P. E. Tilford began a new study of the organisms infecting the vascular tissues of potato plants in the fertilizer and crop rotation experiments. The Fusaria he isolated were predominately weak pathogens, not **F. oxysporum.** Cultures of these species, inoculated onto roots of plants growing thriftily in sterilized compost, usually failed to infect. By 1929 Tilford concluded that plants subject to infection by such weak pathogens must be growing under some unfavorable condition. He also pointed out that not all of the weakly growing plants were infected. (Results unpublished).

The problems, then, of early dying, low yields and discolored tubers were satisfactorily solved for some growers in the state by planting certified seed and spraying, but not for many others, and not in the long continued potato experiments.

Varietal resistance to vascular discoloration. During a number of years, Tilford cooperated in variety testing of potatoes. The prominent late variety of Ohio at the time was Russet Rural. No late variety equalling it in yield was found to have less blackening of the vascular areas until Katahdin became available shortly after 1930. Of the early varieties, the popular Irish Cobbler, when grown regularly from certified seed, was found to be largely free from internal discoloration.

This practical aspect of the problem was solved by adoption of resistant varieties, but problems of premature dying and low yields remained.

FURTHER DIAGNOSIS OF THE PROBLEM

In 1926 the fertilizer experiment started by Thorne in 1894 was assigned to the writer with a directive to find the cause of the unsatisfactory crops of potatoes and to make any changes in treatments or procedures which would result in distinctly better yields.

At the outset the only change in treatments was an increase in nitrogen on two plots. The largest previous application was 50 pounds per acre in a 5-10-20 mixture. This was doubled on the two plots, and one of them was given an additional 40 pound per acre in side dressings. The extra nitrogen increased the growth of tops, but they died down at the same time as the plants receiving 50 pounds, and there was no pronounced increase in yield of tubers.

The only changes in cultural methods were to plow somewhat deeper with the aim of inducing deeper rooting, and to spray the tops more frequently. The resulting average yield for the six years of 1927-32 was only 216 bushels per acre on the best fertilized plots.

Test of minor elements. Although the plants of the fertilizer experiment showed no symptoms characteristic of minor element deficiencies, exploratory tests with applications of borax, and the sulfate salts of manganese, magnesium and zinc were conducted on roadway plots. These roadways had been used only during wheat harvest and had been cropped the same as the experiment plots, but not fertilized. After a uniform application of 4-10-6 at the rate of 3000 pounds per acre in 1928, the minerals were mixed with the soil of small subdivisions of the roadways, singly and as a complete mixture. Application of borax was at the rate of 20 pounds per acre, of the others 100 pounds per acre. No distinct benefit in growth or yield of potatoes was obtained from any of the treatments in 1928, or when repeated on an adjoining block in 1929.

Effect of soil reaction. For other trials a block of land adjoining the fertilizer experiment was made available in 1927. Part of it had been used for a liming experiment with strawberries beginning in 1923. Although several experiments in other states had demonstrated that liming had little effect on the yield of potatoes if ample fertilizer was applied, it seemed advisable to use this area for a soil reaction experiment with potatoes. The possibility that on Wooster silt loam liming might have some detrimental effect which had not appeared in experiments elsewhere was suggested by the early history of the fertilizer experiment. On the long-farmed area lime was applied at the outset for the benefit of the clover, while on the area cleared from forest it was first applied in 1905 following the fourth crop of potatoes. As noted previously, these first four crops were considerably better than those from the long-cropped land or from the virgin area at any time thereafter.

Potatoes were grown, beginning 1927, on the differentially limed plots where strawberries had been previously. As far as known, the block had not been limed prior to 1923 when ground limestone had been applied at rates aimed to produce a range of soil reaction differing by one-half pH units. In 1927 and each year thereafter, the soil of each plot was tested and small amounts of hydrated lime added as deemed needed to maintain the pH of the soil at the desired point. Each crop of potatoes was fertilized uniformly with one ton per acre of 4-10-6. Further details were reported previously, (2).

As shown in Table 3, the soil reaction had relatively little effect on the yield during the five years of the experiment, and the differences indicated that liming was beneficial rather than harmful. The yields during this experiment averaged nearly 50 bushels per acre higher than in the nearby fertilizer experiment, but the difference could not be attributed to the liming treatments.

Results from pot experiments. Supplementary tests with minor elements at double the field rates were made in the greenhouse, using

TABLE 3.—Effect of Liming on Yield of Russet Rural Potatoes

Year	Range in soil reaction during course of five years, pH				
	4.7—5.3	5.2—5.7	5.8—6.3	6.3—6.9	7.0—8.0
	Average yield of duplicate plots, size A tubers, bushel per acre				
1927	278	289	264	311	353
1928	250	279	262	233	242
1929	203	201	208	208	212
1930	177	200	197	183	182
1931	270	283	292	272	297
Average	236	250	244	241	257

soil from one of the well fertilized plots. Again no appreciable benefits from the treatment were noted.

On the other hand, it was the experiences in growing plants in large pots which gave a clue to a soil condition limiting growth and yield in the field.

The first series of pot experiments, started November 10, 1929, were well watered immediately after planting and most of the seed pieces rotted, presumably from being too wet. It was noted, however, that the soil in 12-inch pots settled nearly two inches when it was heavily watered.

In the next series, started February 15, 1930, water was applied more sparingly and none directly above the seed pieces. The plants started well, but during the course of successive waterings the soil gradually settled until again it was almost two inches below its initial level. Thereafter the growth of branches terminated and in a few weeks the leaves turned light green. The plants died within 100 days after planting and the tuber yield was less than one-half pound per pot. Most of the roots were near the walls of the pots, not well distributed through the soil.

To avoid excessive settling of the soil, moisture was supplied by capillarity in the next test, started February 1, 1931. Twelve-inch pots of Wooster silt loam, set in a large pan with water ¾ inch deep, became wetted to the top within 60 hours. The soil settled only about one-half inch. In all treatments the plants grew well, with no consistent differences in growth or yield from the minor elements. More important was the fact that the plants started February 1, remained green until late June, about 150 days from planting, and the average yield of tubers was 1.6 pounds per pot. This was nearly four times the yield of the preceding pot test and 60 percent larger than the yield per hill in the field in the favorable season of 1931. Although roots were somewhat localized near the pot walls they were much more abundant through the body of the soil than in the preceding test with more compacted soil.

These pot experiments, then, suggested that compaction of this soil in the field could be the factor limiting the yield of potatoes.

On the other hand, the excellent growth in the pots watered by capillarity might have been largely due to uniformity of the moisture supply. Before approaching the problem in the field, it seemed desirable to determine whether compacted soil in pots would produce good growth if kept uniformly moist by capillarity.

As compaction in the field could be due either to cultural operations or to heavy rains, a test was planned to compare tamped with water-logged compaction. Seed tubers were planted in 12 pots of air-dry soil, level full when settled by jarring, and the soil slowly watered around the edges with a hose. When the plants were about 8 inches tall, one set of four pots was over-watered with the hose, another set was tamped to the same level, and the third set was left loose, with the surface of the soil about 1½ inches higher than the compacted sets. Thereafter all pots were placed in large pans with water uniformly maintained ¾ inch deep.

The seed pieces had been planted January 28, 1932 and the pots placed in water March 10. A month later the growth of plants in both the compacted sets was noticeably retarded, but they did not die down until arrival of high temperatures in early June. Harvested then, the plants in the water-logged soil had no tubers over two inches in diameter and the average yield was 0.40 pound per pot. In the tamped soil it was 0.53 pound. In the looser soil the tops were still green but growth of branches had terminated, and yield of tubers averaged 1.31 pounds per pot.

In brief, tamping the moist soil was almost as harmful as water-logging, and maintaining uniform abundance of moisture in compacted Wooster silt loam did not insure good growth. The yield of tubers in it was less than half that produced in the loose soil.

Box test of long-cropped vs. virgin soil. Another question for a pot test was whether long cropped soil, properly watered, would actually prove as productive as virgin soil. For the comparison, tight wooden boxes 18 inches square and 12 inches deep were used instead of clay pots. The capacity of the boxes approximated the volume of soil per hill in the field, and no air would reach the roots through the walls. Water was supplied by capillarity through holes bored in the bottoms of the boxes.

Soil was obtained from the fertilizer experiment and from a forest with virgin soil about one-quarter mile distant. Both were sifted through one-half inch screen to break up clods in the long-cropped soil and to remove roots and other coarse matter from the forest soil. Because virgin Wooster silt loam is known to be acid and low in phosphate, hydrated lime and superphosphate at the rate of 0.2 pounds each per hundred pounds of soil were mixed with it. 8-8-8 fertilizer was added to both soils at the rate of 0.05 pounds per hundred. Seed tubers were treated to break their dormancy, and on November 1, 1932, four boxes of each soil were planted with a whole tuber each.

Length of stems and branches were measured weekly and the plants were watched for other differences but none of significance were noted. All grew well. At harvest on April 14, the yield of tubers in the long-cropped soil averaged 1.96 pounds per box compared with 2.04 pounds in the virgin soil. The difference was not statistically significant.

Root distribution in the field. After the pot experiments indicated that soil compaction was restricting root development of potatoes, observations were made at intervals on root distribution in the fertilizer experiment. As in the pots, roots in the field soil were more abundant in the looser portions (Fig. 1 and 2). Clods, both large and small, into which no roots had penetrated were frequently found. Soil nicely crumbled by plowing and well occupied by the early growth of roots was found after prolonged midsummer rains to be more or less slaked and coalesced into compact formations, which hardened with drying. Roots encased in these clods were sometimes found to be dead. In general the subsequent yellowing of the plants was proportional to the volume of soil in a compact state. At harvest, where the plants had yellowed and died early, clods of soil carried over on the digger web (Fig. 3).

As a whole, the field observations agreed with the results of the pot tests, pointing to compaction of the soil as at least a prominent factor in the poor growth and low yields of potatoes on this Wooster silt loam.

Benefit from ventilation of the soil. To determine if aeration of the roots was itself a factor, supplementary aeration in the field was tested by means of ventilating tile lines laid directly under the potato rows. On land adjoining the soil reaction experiment, tile were laid after plowing, in hand-dug trenches 10 inches deep and 50 feet long, (Fig. 4). Two rows were of ordinary 4-inch drainage tile and two of perforated tile. The tile lines opened into ditches at both ends to allow free movement of air. When covered, and the potatoes planted, the tops of the tile were about an inch below the bottom of the seed pieces. As the operation allowed the displaced soil to dry out considerably, the soil of three intervening check rows was similarly shovelled out and replaced before planting. This experiment was conducted in 1933 and repeated in 1934.

Fig. 1.—Typical development of rather sparse roots before main body of soil had become compacted by heavy rain.

Rainfall was moderate both seasons, and, as the soil was well loosened by the shovelling and suffered little compaction from the rainfall, the check rows yielded at the rate of 300 bushels per acre both years. But in both seasons the ventilated rows gave higher yields, the perforated tile better than the plain tile (Table 4).

Directly after harvest the tile lines were dug up and were found surrounded by a network of roots, indicating that roots thrived where air was most abundant.

Although this experiment threw no direct light on the detrimental effects of compaction of the soil, it demonstrated that even when this

Fig. 2.—Characteristic localization of roots after compaction of soil by midsummer rains.

soil is moderately loose throughout the growing season the aeration may not be optimal for potato roots.

TILLAGE TESTS AND MANURING EXPERIMENTS AIMED TO INCREASE AERATION OF THE SOIL

When the pot tests first pointed to compaction of the soil as a factor limiting growth and yield, some field tests were begun which it was hoped would lead to a simple and practical way of keeping the soil loose. These fell in two categories. The first were mechanical and tillage operations aimed to improve drainage or otherwise to minimize

Fig. 3.—Typical cloddy condition of soil at time of digging the fertilizer experiment.

compaction of the plowed soil. The second were experiments incorporating large amounts of organic matter.

Drainage and tillage. It has long been known that in general the productivity of the silt loams at the Ohio Experiment Station is increased by tile drainage. The ten acres used for the potato fertilizer experiment had been tiled in 1894 with lines two rods apart. Later an adjoining block where potatoes were grown after 1926 was similarly tiled. In 1933 new lines were laid between each of the original lines, with help furnished by the Civilian Conservation Corps.

None of this tiling was planned as an experiment, no untiled blocks being left for comparison. No marked increase in the level of yield

Fig. 4.—Installing ventilating tile.

TABLE 4.—Effect of Ventilating the Soil by Means of Shallow Tile Lines Directly Under Potato Rows

Treatment	Average yield of size A potatoes, bushels per acre	
	1933	1934
Check, no tile	312	300
Plain tile	362	328
Perforated tile	381	376

appeared following 1933, and the soil continued to become compacted by prolonged rains.

Harrowing. Beginning in 1932, on the block adjoining the fertilizer experiment, alternate 0.2 acre plots were left unfitted after plowing, the intervening plots being disked and harrowed prior to planting. No significant differences in growth or yield appeared the first two years, which were relatively dry. It was of interest, however, that perfect stands were obtained on the unfitted as well as on the harrowed plots. In 1934, a rain the day after planting caused rotting of the seed pieces in the harrowed soil, reducing the average stand about 25 percent and giving a yield of 192 bushels compared to 230 on the unfitted soil. Thereafter, all experiments were planted directly after plowing with no harrowing.

The soil thus handled remained loose enough to insure good sprouting of seed pieces, but it did not withstand compaction from midsummer rains.

Subsoiling. Loosening the subsoil almost to the depth of the drainage tile was first tested in 1931. An implement with a single prong extending about 20 inches below the plow furrow was attached behind a one-bottom 18-inch plow, the furrows running at right angles to the tile lines. Two 30-foot strips were thus loosened across the block of the fertilizer experiment to be in potatoes that year. This subsoiling under each furrow raised the surface of the blocks three to four inches above the level of the check strips.

Although 1931 was a relatively dry year the loosened soil gradually settled until after an August rainfall of 4.88 inches its surface was not noticeably above that of the check strips. No roots were found extending into the loosened subsoil. The average increase in yield was only ten bushels per acre.

Effective subsoiling can only be done when the soil is dry enough to crack and crumble. Not until 1936 was it again in this condition at the time of spring plowing. Again, the increase in yield averaged ten bushels per acre.

When subsoiling was tried a third time in 1946, rain started shortly after planting and continued for a total of 14 inches in eight weeks. If subsoiling was to be beneficial because of accelerated drainage, this was the year for the benefit to stand out. No indication of such benefit was noted from the growth of the plants, the depth of roots, or the yield of tubers. After the heavy rains the loosened subsoil was found to be coalesced and almost indistinguishable from undisturbed areas.

Hilling. In the irrigated West, applying water by flooding potato fields has long been known to be detrimental; the established practice is to hill the rows and run water in the intervening furrows. In Ohio, potatoes are sometimes hilled as a method of combatting weeds, but it is not a standard practice. As a means of preventing soil compaction, it seemed that hilling might divert some of the rainfall, leaving the soil of the ridges in better condition for potatoes.

Hilling was tested several seasons, including the exceptionally wet year of 1936. As shown in Table 5, there was no conspicuous benefit in any season.

Incorporation of Large Amounts of Organic Matter

In 1933, when the benefit from ventilating the soil was demonstrated, the opinion prevailed that the way to improve tilth and increase the aeration of soil was to incorporate large amounts of organic matter judiciously supplemented with lime and nitrogen fertilizer. In the long continued fertilizer experiment, however, certain plots had received 16 tons of manure per acre every time potatoes were grown in three-year

TABLE 5.—Effect of Hilling Russet Rural Potatoes Planted About the Middle of May

Year of test	Yield in bushels per acre		Increase due to hilling
	Level	Hilled	
1936	296	266	—30
1937	183	195	12
1939	184	185	1
1941	142	126	—16
1946	238	230	— 8
Average	208	200	— 8

rotation and had failed to maintain good production over the 40-year period, (data in Table 1). Organic matter to solve the problem must either be applied in larger amounts, or be of different character from manure, or perhaps both.

Test with chopped corn stover. To test the effect of coarse organic matter, incorporated in such volume that it might increase the aerating channels in the soil, chopped stover was disked into square-rod plots at three rates of application in 1934. In each case, half was worked in before plowing, half afterwards, by means of a 22-inch crop disk. The largest amount that could be worked in was 13.5 tons per acre, even when applied and disked a little at a time. Potatoes were planted immediately, fertilized with 1500 pounds per acre of 8-8-8. As shown in Table 6, the presence of the two larger amounts of chopped stover considerably increased the yield of potatoes in 1934, which was a dry season. Repeated in 1935, when nine inches of rain fell in July and another nine inches in August, the results were again promising.

Although no attempt was made to measure the porosity of the soil or to determine the presence of aerating channels, it was observed at time of harvest that parts of a soil containing stover remained distinctly porous even after the deluges of 1935, and that the heaviest applications largely dominated the gross structure.

Test of green manures. The promising results from this test of chopped stover suggested that similar good yields might be obtained from plowing down very large quantities of green manures. An experiment with green manures had been started in 1931 to compare five distinctly different crops, to be grown one year and plowed down for late potatoes grown the alternate years. After the chopped stover tests, the plan was not altered except that all the green manures were

TABLE 6.—Effect of Mixing Chopped Corn Stover in the Soil

Average yield of duplicate plots of Russet Rural potatoes planted in late May.

Chopped stover per acre tons	Yield per acre, bushels	
	1934	1935
None	287	194
4.5	286	254
9.0	337	289
13.5	399	310

allowed to grow as large as possible before plowing down, (Fig. 5 and 6).

This experiment was located on land that had been in sod for four years and in bush fruits for several years previously. The soil was Canfield silt loam, similar to that used by Williams for crop rotation experiments. The crops grown to plow down were corn, buckwheat, soybeans, alfalfa and sweet clover, with rye as winter cover crop following the three annuals. A second plot of corn was included to which supplementary sulfate of ammonia was applied after the corn was plowed under in late September. A second plot of soybeans, not followed by rye, was also included. The rye sown after the annual green manures was allowed to grow 4 to 5 feet tall before plowing for potatoes in late May. As shown in Figures 5 and 6, the tall crops were

Fig. 5.—Plowing down drilled corn containing about five tons of dry matter per acre.

successfully plowed down with a one-bottom plow drawn by a track-type tractor.

After the harvest of potatoes in October, rye was uniformly sown on all plots. It served as a nurse crop for sweet clover and alfalfa, being clipped to encourage their growth. Where corn, buckwheat and soybeans were to be planted this rye was plowed down in late April or early May. The buckwheat was disked in midsummer and a second crop planted. As the land was well limed, the potatoes uniformly fertilized, with 1500 pounds per acre of 4-10-6, and the corn and buckwheat given an application of 200 pounds per acre of sulfate of ammonia, the green manure crops grew well. An exception was the midsummer planting of buckwheat, which did not start well in hot soil. The weight of the green manures was calculated from square-yard samples, collected immediately ahead of plowing, oven dried and

Fig. 6.—Winter cover crop of rye allowed to grow until it contained nearly three tons of dry matter per acre.

weighed. An aliquot was analyzed for total nitrogen. The samples of sweet clover and alfalfa included the fleshy roots; of all other crops, only the above-ground parts were collected.

The experiment consisted of two parallel series of 0.02-acre plots without replication, but with sweet clover plots at each end. One series was in potatoes while the other was in green manures

Continued for 16 years, through 1946, none of the treatments maintained good production, (Table 7). At the outset, the plowing down of the large crops of corn and rye looked promising for four years, then the potato yields progressively declined, even on Plot 5 where the green manures supplied over 16,000 pounds of organic dry matter per acre alternate years. During the second eight years the yields were regularly poor. Thus, bulky crops turned under proved no better than sweet clover, which supplied less than half as much organic matter on a dry-weight basis.

The question at this point is: Why did the barnyard manure and the green manures fail to give the same benefit as obtained from mixing chopped corn stover in the soil? Possibly the chopped corn stover was

TABLE 7.—Dry Matter and Nitrogen in Green Manure Crops and Average Yield of Potatoes

Plot	Green manure		Average components of green manures when plowed down, pounds per acre				Potatoes, Size A. Average annual yield, bushels per acre	
			Crops plowed in fall		Crops plowed in spring*			
	Principal crop	Winter crop*	Dry matter	Nitrogen	Dry matter	Nitrogen	First 8 yrs. 1931-1938	Second 8 yrs. 1939-1946
1	Sweet clover				5,892	170	209	167
2	Soybeans	None	4,636	112			214	117
3	Soybeans	Rye	4,677	113	4,992	68	232	111
4	Corn	Rye	10,659	108	3,853	50	258	134
5	Corn, N†	Rye	10,578	114	5,740	87	276	147
6	Buckwheat, N†	Rye	4,412‡	99	6,222	98	267	135
7	Alfalfa				3,734	99	263	168
8	Sweet clover				5,734	165	267	203

*Includes only the rye plowed down prior to potatoes. The rye planted on all plots after potatoes, clipped or plowed when less than two feet tall, averaged about 2,000 pounds of dry matter with 48 pounds of nitrogen per acre.

†Sulfate of ammonia drilled deeply at rate of 380 pounds per acre after plowing down corn and summer planting of buckwheat.

‡Data on buckwheat includes that of both spring and summer planting.

applied in such volume, and so mixed with the soil, that it largely dominated the structure, whereas the manures plowed down lay in the soil in layers or bands. Several attempts were made to mix the green manures with soil by disking prior to plowing. The volume of the corn and the tall rye, however, was such that a heavily weighed 22-inch disk did not cut them up well, to say nothing of mixing them into the soil. Consequently, the plowing down was continued as pictured in Figures 5 and 6 to determine if an accumulation of organic residues would prove beneficial in the course of time, particularly where the large volume of corn turned under was regularly fortified with nitrogen fertilizer.

The supplement of sulfate of ammonia, however, was of little value during the last eight years. It increased the growth of the rye planted following the cor nand buckwheat, but no change in the color of the soil, or improvement in tilth, was noted, and the effect on the potato crops was negligible.

Test of 24 tons of manure per acre. The original fertilizer experiment was discontinued after 1932 and the land left in sod for six years. Then it was reestablished on part of the same block as a test of modern fertilizer applications on early potatoes. Started as a two-year rotation with corn plowed down as green manure, the plan was changed after two years to potatoes every year. The previously manured plots were remanured prior to each crop of potatoes at their previous rates, and an increased application of 24 tons per acre was applied to an adjoining, previously unfertilized and unmanured plot. The early variety grown was Irish Cobbler.

Extra precautions were taken to avoid compaction of the soil by the cultural operations. After harvest in late August, rye was sown as a winter cover. The rye roots occupied the soil well, even where it had been cloddy at harvest. In the early spring the rye plowed like a sod, and the block was planted to potatoes without harrowing. The planter was drawn by a track-type tractor. The experimental block was narrowed to 55 feet so that the plants could be sprayed with an orchard sprayer drawn along roadways at each side. In spite of these precautions the soil became compacted by heavy rains.

The experiment was continued for twelve years. For the first three years the yields on the heavily manured plots, and on the well fertilized plots, averaged over 300 bushels per acre. Then they began to decline. As shown in Table 8, the well manured plots during the last six years averaged 189 bushels per acre. Although this average was better than obtained from the fertilized plots here, yields on another block during these same six years averaged 480 bushels per acre, (Date given later in Table 13).

MEASUREMENTS OF THE POROSITY OF THE SOIL

Beginning in 1938, the pore space of the experimental plots was measured annually just prior to harvest of the potatoes. The aim was to determine which, if any, of the treatments tended to increase the total pore space in the soil. The study was stimulated by the discovery of Havis and Gourley (8) that some long continued treatments of nearby orchards had resulted in marked differences in the porosity of the soil.

Minimum porosity tolerated by potato roots in clods. As a starting point for reasoning on the amount of porosity required by potato

TABLE 8.—Comparison of Manure with Fertilizer on Yield of Early Potatoes

Plot	Manure or fertilizer applied per acre	Average annual yield of size A potatoes, bushels per acre	
		1938-43	1944-49
30	Manure, 8 tons	182	144
32	Manure, 16 tons	269	189
33	Manure, 24 tons	254	189
31	Fertilizer 1000 lbs 8 8 8	251	151
23	Fertilizer 1000 lbs 8 16-16	251	170

roots in this silt loam, the threshold or minimum porosity was determined from a study of clods. As mentioned in the introduction, clods without living roots are commonly present in this soil. A number of these were collected, together with a few that had living roots, (Fig. 7). Some very hard clods were also examined to learn how compact this soil may become in the field.

The procedure was to collect a few such clods at times when the soil was fairly dry, placing each in a small tight can to retard drying of the surface. In the laboratory, working with one at a time, the outer portion was shaved away to leave a spherical shape, the shavings being used for moisture determination. The spherical clod was promptly weighed, suspended by an encircling thread, then dipped in low melting-point paraffin of known density and reweighed. Next it was weighed suspended in water. These data gave its volume weight. Afterward

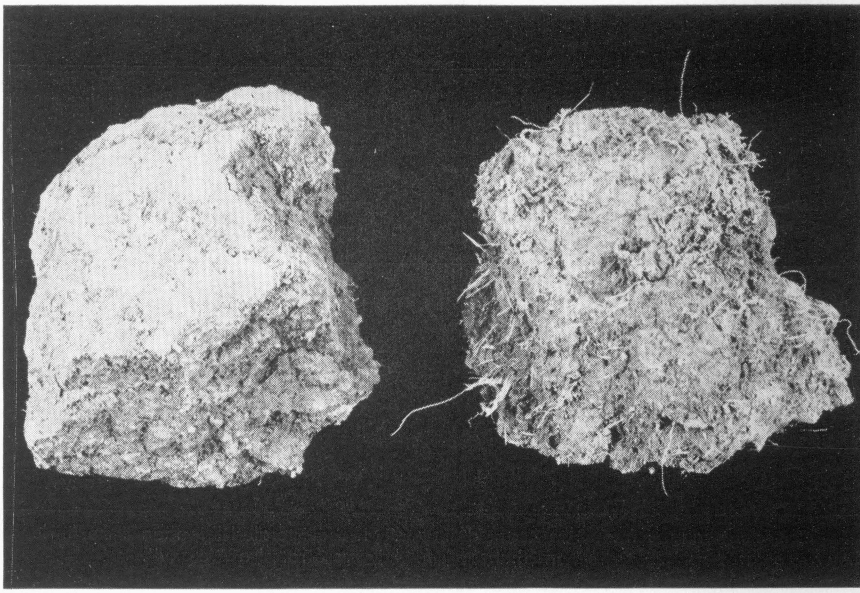

Fig. 7.—Clods with and without roots.

each clod was crumbled and if stones were found, or if the structure did not appear to be fairly homogeneous, its data were discarded. A dozen or more clods were thus weighed each year from 1940 through 1942.

To convert volume weight into terms of pore space it was necessary to know the density (specific gravity) of the soil. This was determined by the pycnometer method on six samples of Wooster and six of Canfield soil. The densities ranged from 2.60 to 2.67; the Wooster silt loam averaging 2.65, the Canfield 2.63.

The calculated pore space of 43 clods is shown by their frequency distribution in Table 9. No seasonal differences were noted. According to these data, the threshold at which the compactness of the soil prevented the entrance or survival of potato roots was near the point of 47 percent of total pore space. Only one clod with less than 47 percent had roots, and only one with more than 47 percent was without them. Moreover, as would be expected, roots were more abundant as clods increased in porosity.

Determinations of Total Pore Space

For measuring the average total pore space of field soil, samples were taken with an implement, patterned after the design of Coile (5),

TABLE 9.—Relation of Total Pore Space in Clods to the Presence of Potato Roots

A. Frequency distribution of 43 clods according to their pore sapce			B. Abundance of roots in individual clods having more than 46.5 % pore space	
Range in per-cent of total pore space	Number in each class			
	Without roots	With roots	Pore space, %	Roots*
35.1—37.0	2		46.7	few
37.1—39.0	1		46.8	none
39.1—41.0	6		47.1	none
41.1—43.0	10		47.2	few
43.1—45.0	12		47.6	some
45.1—47.0	5	1	47.7	some
47.1—49.0	1	4	47.9	some
49.1—51.0		1	51.0	many

*The clods ranged from 3 to 4 cm. diameter. If roots totaled less than 4 cm. in length they were rated as "few", if more than 15 cm. they were rated as "many".

which removed a cylindrical core three inches in diameter and three inches deep with little or no disturbance of the soil structure. The top four inches of soil were first carefully shovelled off, so that the cores sampled represented a depth of four to seven inches. Wherever potatoes were being grown, the depth of plowing was 10 to 11 inches, hence the samples were taken approximately at mid-depth. When soil was being removed from the sampling cylinder, it was crumbled by hand, and if stones over one-inch, or large masses of organic matter, were present the sample was discarded.

After oven-drying, the soil of each core was weighed and its volume calculated. No determination was made of the organic matter present; the total weight of the dry soil was assumed to have a density of 2.65 (or 2.63 if Canfield) and its volume calculated accordingly. The volume of dry soil deducted from the total volume gave the total pore space. In the following discussions, these volumes are expressed as percentage of total volume of the cores sampled.

Preliminary studies showed the soil at time of planting usually averaged 55 percent or more of total pore space. The data of most interest were the pore spaces retained after heavy rain, the samples being collected when the soil had dried down sufficiently to lose plasticity. After the first two years, samples were collected only late in the season, shortly before harvest. Most of the data of the following tables are averages of five determinations on each plot.

Green-manured soil. During the last seven years of the green-manure experiment the pore space of all plots planted to potatoes was measured just prior to harvest. The total pore space was found to range from a low of 45.1 to a high of 50.6 percent of the volume of the soil. No green manure, however, was consistently superior to any other in its effect on soil porosity year after year. None of the treatments appeared to be increasing the porosity during the period, and correspondingly there was but little correlation with the average yield of potatoes, (Table 10). More important, the average total pore space was not much above 47 percent, indicated by the clod study as the minimum for potato roots in this soil. Correspondingly, much of the soil in all plots was devoid of roots, (as pictured in Fig. 2).

Manured soil. Similar levels of total pore space were found in the fertilizer experiment begun in 1938 with early potatoes followed by cover crops of August-sown rye. From the viewpoint of soil structure, the manured plots were of most interest, particularly the plot given 24 tons per acre every winter. The pore space of this manured soil dropped below 50 percent after the first two seasons, and averaged only 48.5 percent for the nine-year period. In comparison, a well fertilized, unmanured plot averaged nearly the same—48.0 percent (Table 11).

During the course of this experiment, it was incidentally noted that the soil became most compacted when heavy rain was followed some time later by drouth. Thus in the continued wet season of 1947 the soil did not become as dense as in 1946.

TABLE 10.—Total Pore Space Found in Soil Prior to Harvest of Potatoes in the Green-manure Experiment

Average of data of 7 years, 1940-46

Crops plowed down	Plot No.	Total pore space in soil, %	Annual yield of potatoes per acre, bu.
Corn, N*, rye	5	48.8	159
Sweet clover	1	48.5	175
Sweet clover	8	48.4	198
Buckwheat, N*, rye	6	48.4	142
Corn, rye	4	48.4	139
Alfalfa	7	48.0	173
Soybeans, rye	3	47.8	117
Soybeans, no rye	2	47.2	120

*Supplementary nitrogen fertilizer applied at time of plowing down crop.

TABLE 11.—Effect of Annual Manuring on Soil Porosity and on Yield of Early Potatoes

Data of Plot 15, fertilized with 1000 pounds per acre of 8-16-16, and of Plot 33, manured at rate of 24 tons per acre prior to each crop of potatoes.

Year	Rainfall, inches				Total pore space of soil, average percent		Yield, size A potatoes, bushels per acre	
	May	June	July	Aug.	Fertilized	Manured	Fertilized	Manured
1938	4.40	4.71	3.83	3.56	50.3	50.1	357	272
1940	4.11	5.77	4.02	5.12	49.4	50.1	320	343
1941	2.96	3.71	5.73	3.35	48.1	49.0	280	287
1942*	3.73	3.33	2.12	1.32	49.0	49.0	250	237
1943	6.27	0.88	5.72	3.44	47.6	47.4	115	123
1944	6.07	3.53	1.24	3.38	46.4	46.8	82	92
1945	4.81	4.79	2.92	1.75	48.1	48.3	258	249
1946	7.16	7.06	2.97	1.26	46.1	47.4	180	232
1947†	5.74	10.04	3.65	7.06	48.1	49.0	117	125
1948*	3.55	5.45	1.45	2.10	49.5	49.7	172	173
Average of 9 years, 1940-1948					48.0	48.5	179	196

*Seasons of relatively light rainfall and less than usual compaction of the soil. Drouth in July and August probably reduced yields.

†In the wet season of 1947 the soil never dried enough to result in hard clods but roots were largely restricted to the top five inches.

Soil under old sods and straw mulches. Soil with a higher proportion of pore space than found in any of the potato experiments was discovered by Havis and Gourley in 1936 in apple orchards left in sod, or mulched with straw (8). Their findings, reported in terms of volume-weight of the soil, are also given in terms of pore space in Table 12. In both orchards the soil under sod and under mulch had more porosity than where cover crops were disked in.

To confirm their findings, samples were taken from the sod of Orchard C in August, 1947, a season of heavy rain. Samples were also collected from sod of an 11-year old peach orchard and a six-year open field adjoining the green manure experiment. The total pore space under these sods ranged from 50.2 to 51.1. The dominant grass of the sods was bluegrass.

YIELD OF POTATOES AFTER SODS

These conditions of high porosity having been found, opportunities were sought to grow potatoes on land that had lain in sod for many years. An ideal site appeared in 1944, where a cherry orchard was

TABLE 12.—Volume Weight and Porosity of Soil from Orchard Plots Given Three Different Treatments

In Orchard "A" straw mulch and sod started 1899, cover crops started 1927. In Orchard "C" all treatments started in 1915. Cover crops of soybeans were disked in fall, rye disked down in spring. Soil cores taken in 1936. Data from Havis and Gourley (8).

Treatment	Volume weight*		Total pore space*	
	Orchard A	Orchard C	Orchard A	Orchard C
Cover crops	1.350	1.328	49.6	50.4
Blue grass sod	1.291	1.261	51.8	52.9
Straw mulch	1.235	1.202	53.9	55.1

*Volume weight was determined on air-dry basis; the pore space was calculated on the assumption that air-dry soil had 1 % moisture, and density of 2.65 when dry.

being removed. Prior to the planting of the cherries a variety collection of potatoes had been grown on this block in 1927, and then repeated in 1928 between the newly set trees. The yields averaged about 250 bushels per acre. A grass mixture was then seeded. Sixteen years later, when the trees were being removed, bluegrass predominated, and at a depth of 4 to 7 inches the soil averaged 52.4 percent of pore space.

A variety collection of potatoes was grown on this block for six successive years, with average yields as shown in Table 13. For five years the pore space remained above 49 percent, and the average yield during thse five years was 526 bushels per acre. Then in the sixth year the yield dropped to less than half that amount.

To show that the excellent yields on this block during the first five years were not due to exceptionally favorable seasons, the data on yield and pore space from the best plots of the fertilizer and the green manure experiments for these years are included in Table 13. Although these other experiments were planted earlier than the variety collection on the cherry orchard block, they were similarly fertilized and sprayed. The much higher yields of the variety collection is a strong indication that its soil was in superior condition for potatoes.

As mentioned previously, a similar pattern of maintenance of good yields for the first few crops of potatoes following long standing sods was noted in three earlier experiments. For convenient reference, the yields of six successive crops of potatoes from all the experiments started on sods are assembled in Table 14.

TABLE 13.—Yield of Potatoes and Porosity of Soil Following a Sod Orchard

For comparison, data of the same years from the fertilizer and the green-manure experiments. Yield per acre of size A potatoes. Average total pore space determined just prior to harvest.

Year	After cherry orchard		Fertilizer experiment Plot 15		Green manure experiment Sweet clover plot	
	Yield	Pore space	Yield	Pore space	Yield	Pore space
	Bu.	%	Bu.	%	Bu.	%
1944	410	54.4	82	46.4	56*	47.8
1945	520	51.0	258	48.1	196	48.0
1946	472	50.1	180	46.1	208	46.7
1947	554	49.8	117	48.1		
1948	680	50.5	172†	49.5		
1949	246	48.6				

*In 1944 the green-manure experiment was planted just ahead of heavy rains which caused considerable rotting of the seed pieces. The orchard block was planted afterwards.

†In 1948 early-planted potatoes in the fertilizer experiment suffered from midsummer drouth; the later planted ones of the ex-orchard block survived the drouth better and made excellent growth thereafter.

In this connection it might be suggested that the superior yields obtained in the liming experiment (Table 3) may have resulted from the presence of straw used for winter protection and for pathway mulch on the strawberries for four years preceding the potatoes. Havis and Gourley found that soil under straw mulch was fully as porous as that under sod (Table 12), and this was later confirmed in a comparison of a six-year mulch with adjoining six-year sods, (Data in Table 17).

SUPPLEMENTARY STUDIES ON THE PHYSICAL CHARACTERISTICS OF WOOSTER SILT LOAM

To learn something further about the structure of Wooster silt loam when in favorable and unfavorable condition for potatoes, a few other physical measurements were made. It is known as a soil with excellent capacity to retain moisture by capillarity, a characteristic attributed to its high proportion of silt. Its mechanical composition is illustrated by the analyses of Table 15.

Proportion of water-stable aggregates. When regularly cropped, Wooster silt loam is rated a soil with relatively small proportion of water-stable aggregates. In orchard soils, however, Havis found a fairly larger proportion, and considerably more under sod than where

TABLE 14.—Yield of Successive Crops of Potatoes on Land Cleared from Forest, Previously in Sod, or Previously Mulched with Straw

Cleared from forest. Rotation with wheat and clover		Four-year sod. Corn and rye plowed down alternate years		Six-year sod. After 1939, rye as winter cover crop		Sixteen-year sod, in orchard. Rye as winter cover crop	
Year and yield in bushels per acre							
1896	243*	1932	247*	1938	357*	1944	410*
1899	205*	1934	289*	1940	320*	1945	520*
1902	373*	1936	274	1941	280	1946	472*
1905	260*	1938	334*	1942	250	1947	554*
1908	185	1940	214	1943	115	1948	680*
1911	142	1942	80	1944	82	1949	246

*Yield more than 2½ times the state average for the respective year.

cover crops were annually disked in, (Table 16). As would be expected the percentage of aggregates correlated with the pore space found previously.

Havis' determinations were made by wet-sieving air-dry samples through nests of six sieves with openings ranging from 2.0 to 0.5 millimeters, using a washing machine designed by Yoder (19). As the initial sieving retained sand and five gravel as well as aggregates, the separates, after drying and weighing, were treated with a solution of sodium oxalate to destroy the aggregates, and the wet-sieving repeated

TABLE 15.—Mechanical Analysis of Wooster Silt Loam from Potato Fertilizer Experiment

Data of Selby and Ames (14) on air-dry samples, collected prior to 1904, from unfertilized Plot 31, adjoining manured Plot 32.

	Section A Farmed prior to 1894	Section C Cleared from forest, 1894
Gravel; over 2 mm.	0.31	3.62
Sand, medium to very coarse; 2.0 to 0.25 mm.	2.41	3.41
Sand, fine and very fine; 0.25 to .05 mm.	17.89	18.06
Silt; 0.05 to 0.1 mm.	71.69	67.70
Clay	2.93	5.10
Total mineral matter, not including gravel	94.92	94.27
Moisture	1.20	1.31
Loss on ignition	4.07	4.94

TABLE 16.—Amount of Water-stable Aggregation in Wooster Silt Loam under Two Methods of Orchard Culture

Dry weight of aggregates per 100 grams of air-dry soil. Data of Havis (7).

Cultural system	Apples, 1915	Apples, 1927	Peaches, 1935
	Kind of trees, and year treatments started		
	Soil aggregates over 0.5 mm., 1942, grams		
Cover crops disked down	14.14	22.46	21.84
Bluegrass sod	43.54	34.16	30.54
	Total pore space in plowed horizon, 1936*, percent		
Cover crops disked down	50.4	49.6	48.8
Bluegrass sod	52.9	51.8	50.8

*Pore space in apple orchards from Table 12. Pore space in peach orchard determined by writer in 1947.

to determine by difference the percentage of the soil initially in the aggregated form.

Using Havis' procedure, soils where potatoes were being grown were analyzed in 1947. Preliminary tests, however, showed that in poorly aggregated soil the volume of separates on the finer sieves retarded the movement of water through the nest as a whole; in the course of 30 minutes washing (as used by Havis) the separation was not complete, small particles were still to be seen on the large sieves. Since Havis' data indicated that porosity was due to the presence of coarse aggregates, and this view is supported in literature reviewed by Baver (1), it seemed reasonable to disregard fine aggregates, (Havis' data in Table 16 include only those over 0.5 mm.). With the omission of screens smaller than 0.25 millimeters the wet-sieving was completed in 30 minutes.

For comparison, samples from more porous soils were analyzed. Without presenting the classification of the sizes of the aggregates found, the data are summarized in Table 17. As anticipated, the proportion of aggregates correlated fairly well with the total pore space.

In agreement with the data of Havis, and of Hopp and Slater (9), soil left in sod had considerably more aggregation than where cropped. Moreover, where potatoes yielded well the fourth and fifth years after sod the amount of aggregates was about twice that found where green manures were being plowed down, and somewhat larger than where manure had been applied annually for eight years. As an indication of

TABLE 17.—Amount of Coarse Aggregates in Soil Variously Treated

Grams per 101 grams of air-dry soil. Samples collected in late August, 1947.

Crop or cover, and material plowed into the soil, if any	Total pore space in soil	Dry weight of aggregates Over 0.5 mm.	Dry weight of aggregates Over 0.25 mm.	Total separates Over 0.5 mm.
	%	gm.	gm.	gm.
Forest	54.0	47.6	53.9	59.8
Straw mulch, orchard 32 years	55.0	67.0	70.8	73.2
Straw mulch, orchard, 12 years	54.5	23.3	34.3	28.2
Straw mulch, open field, 6 years	51.1	11.8	16.2	21.5
Sod, orchard, 32 years	50.3	14.4	24.9	27.5
Sod, open field, 6 years	50.2	10.8	14.3	15.5
Potatoes, 4th year after sod	49.8	6.2	11.9	13.1
Potatoes, 5th year after sod*	50.1	5.0	9.0	11.4
Potatoes, 24 tons manure†	49.0	3.7	8 0	8.8
Potatoes, 16 tons manure†	48.8	3.7	7.4	8.7
Potatoes, 8 tons manure†	48.2	3.9	6.7	10.3
Potatoes, no manure	48.1	2.4	4.5	6.3
Potatoes, corn, nitrogen, rye‡	48.0	2.3	4.4	6.4
Potatoes, corn, rye‡	47.4	3.0	5.0	7.8
Potatoes, sweet clover‡	46.8	4.0	6.3	8.8
Correlation with total pore space, %		83.0	86.5	71.5

*Sampled and analyzed September, 1948.

†Amount of manure applied annually for 8 years.

‡Green manure crops plowed down alternate years for a period of 16 years. "Nitrogen" refers to sulfate of ammonia applied when corn was plowed down.

the minimum for good crops of potatoes in Wooster silt loam, there was 9 percent of water-stable aggregates over 0.25 millimeters in the fifth and last year that high yield was obtained following the cherry orchard sod.

Compaction when wetted and when water-logged. From field observations it was suspected that the silt loam of the experimental area became seriously compacted only when wetted to the point where some free water was present. This deduction was supported by laboratory demonstration of the sequence of settling with wetting. Soil from the fertilizer experiment was first sifted through a five-millimeter screen to remove coarse material, then the fine particles were removed through a one-millimeter sieve. Thus screened, it was poured into glass cylinders, with light tamping, until 20 centimeters deep. Water dripped into cylinder "2" of Figure 8 slaked the surface particles, washing some fine material downward as much as five centimeters. The slaking of the surface prevented the escape of air trapped beneath, and the test was repeated with a tube as shown, extending to the bottom for the air to escape. The slaked surface, however, retarded infiltration; below the top five centimeters the wet front appeared to move downward by capillarity. When the front reached the bottom, if no further water was added, there was relatively little slaking and settling below the top five centimeters.

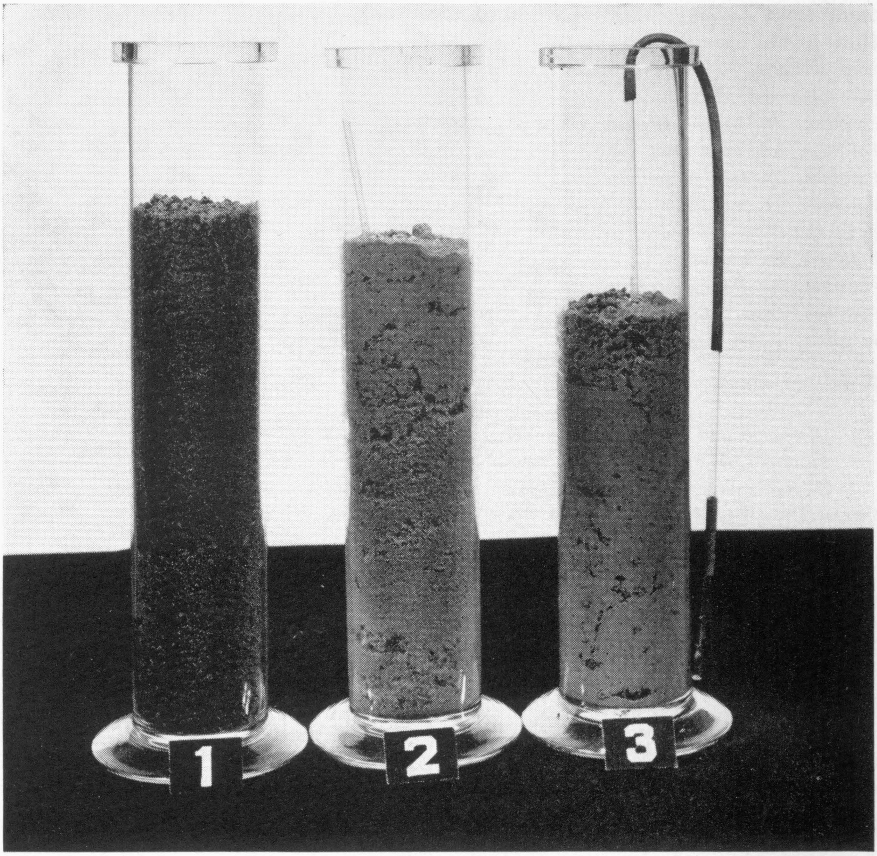

Fig. 8.—Effect of degree of wetting on compaction of Wooster silt loam.

1. Not wetted; settled by jarring. Pore space 58 percent.

2. Wetted by slowly dropping water on top until wet front reached bottom. Pore space 55 percent.

3. Wetted by flowing water in through tube until water covered top of soil, then siphoning out the free water. Pore space 46 percent.

In cylinder "3" the soil was first similarly wetted on top until the wet front reached the bottom, then more water was slowly introduced at the bottom through the tube. As the water level rose the soil could be seen slaking and settling. Presumably then, this type of settling occurs in the field only when and where free water accumulates in the plowed horizon.

Just as soil with a higher proportion of water-stable aggregates did not become seriously compacted by rains, so also a sample water-logged in a cylinder slaked and settled very little (Fig. 9).

Proportion of pore space occupied by water at low tensions. Throughout the preceding pages the pore space of the soil has been expressed as percentage of the total volume, without reference to the amount occupied by water. To illustrate the volume of water held by Wooster silt loam, the moisture content at tensions of 3 foot and of 8 inches was determined in Richard's pots, and also the amount absorbed by clods one-centimeter thick placed on a saturated blotter. From these determinations the volume of water per 100 milliliters of soil was calculated as listed in Table 18. The pore space unfilled by water is listed as air space.

As preceding data indicated a minimum of 49 or 50 percent of total pore space to insure good yields of potatoes on this silt loam, the calculations for these values in Table 18 are of special interest. Thus if a soil with 50% of total pore space were wet to the same degree as a clod on a saturated blotter, 43.7 percent would be filled with water leaving only 6.3 percent for air. Or again, if the same soil were in equilibrium with a water table at three feet, the depth of well laid tile, it would have 31.3 percent of its volume occupied by moisture leaving 18.7 percent for air.

Because the clod study (Table 9) indicated that 47 percent of pore space was the threshold at which roots occupied Wooster silt loam, it is also of interest to note, in Table 18, that when soil with 47 percent of pore space is close to a water table (and has 33 percent of moisture by weight) 46.4 percent is occupied by water, leaving less than 1 percent for air. It seems reasonable to presume that rain percolating through the soil would similarly wet it, and the lack of air at such times may be the reason for the failure of potato roots to penetrate or to survive.

STUDIES ELSEWHERE ON PORE SPACE IN POTATO SOILS

Pore space requirement in pail tests. Dunn and Lyford studied the interrelation of soil texture and moisture on the yield of potatoes, (6). In 14-quart pails, the soils were first tamped to give a range in total pore space, then weighed and watered to give a range in moisture

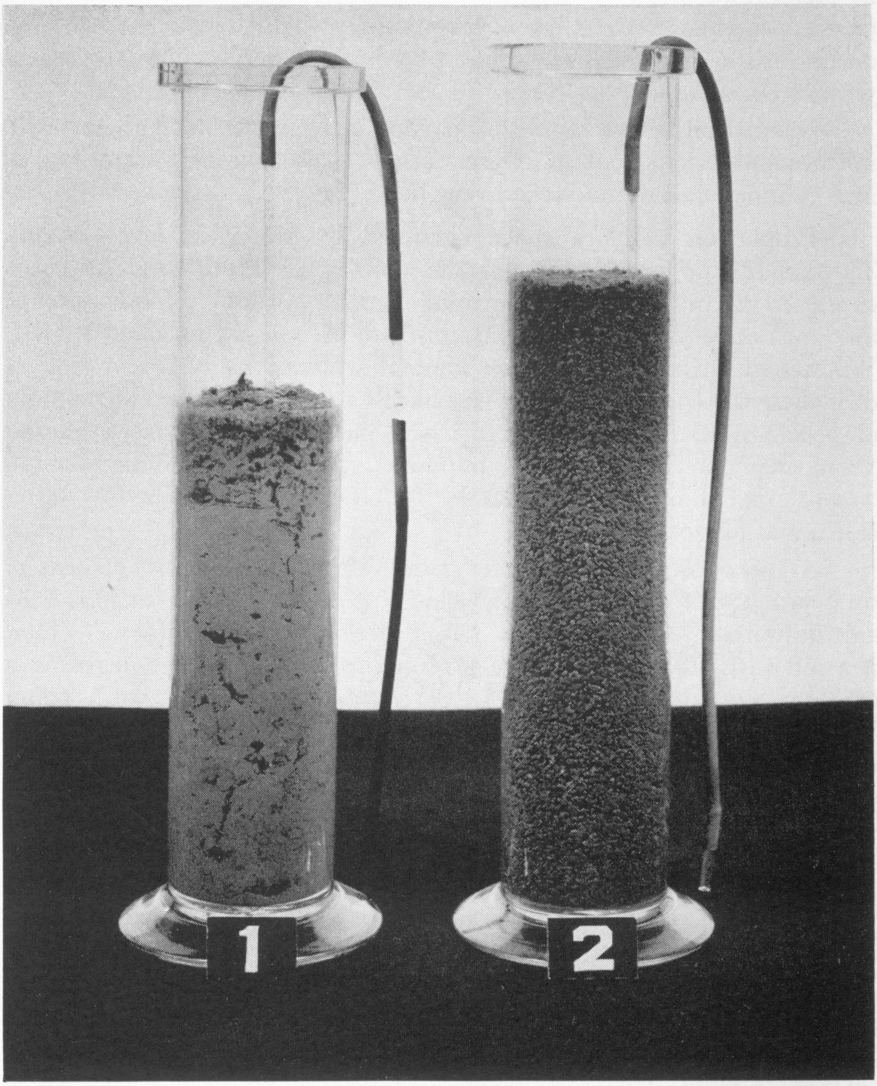

Fig. 9.—Effect of degree of aggregation on the retention of porosity after water-logging and draining.

Both cylinders filled to same level with Wooster silt loam sifted into one to five millimeter separates.

1. Soil from fertilizer experiment, having less than 4 percent of macro-aggregates.

2. Soil from under straw mulch in nearby orchard, with more than 30 percent macro-aggregates.

TABLE 18.—Interrelation of Moisture and Total Porosity to the Pore Space Available for Aeration in Wooster Silt Loam

Calculations based on a core volume of 100 milliliters, and soil density of 2.65.

Total pore space	Volume occupied by soil	Dry weight of soil	0.2 inch above water table; moisture 33%		8 inches above water table; moisture 29.0%		3 feet above water table; moisture 23.6%	
			Vol. of water	Air space	Vol. of water	Air space	Vol. of water	Air space
ml.	ml.	gm.	ml.	ml.	ml.	ml.	ml.	ml.
47	53	140.5	46.4	0.6	40.7	6.3	33.2	13.8
48	52	137.8	45.5	2.5	40.0	8.0	32.5	15.5
49	51	135.2	44.6	4.4	39.2	9.8	31.9	17.1
50	50	132.5	43.7	6.3	38.4	11.6	31.3	18.7
51	49	129.9	42.9	8.1	37.7	13.3	30.7	20.3
52	48	127.2	42 0	10.0	36.9	15.1	30.0	22.0
53	47	124.6	41.1	11.9	36.1	16.9	29.4	23.6

content. As they were tamped only when fairly dry, in no instance was the total pore space less than 50 percent.

In Newmarket fine sandy loam, if the moisture was less than 28 percent by weight, it appeared to limit yield. With more than 28 percent of moisture, the results, listed in Table 19, indicated that the air space of 11.6 percent may have been insufficient. On the other hand, with 12.8 percent the yield of tubers was as high as in any of the soils with more air space.

TABLE 19.—Effect of Pore Space and Moisture in Soil on Yield of Potatoes Grown in 14-Quart Pails

Data of Dunn and Lyford (6) with Newmarket fine sandy loam.

Pore space in soil: Total	Pore space in soil: Available for air	Soil moisture by weight	Yield of tubers per pail
%	%	%	gm
50	11.6	29.0	610
55	12.8	35.4	720
60	15.9	43.5	705
55	18.5	30.6	660
60	20.1	37.6	665
55	21.4	28.2	690

Comparing three soils differing in texture, all having about 60 percent of pore space, and maintained with 30 percent or more of moisture, Dunn and Lyford obtained as good yields from Buxton silty clay loam as from Merrimac loamy sand, but about ten percent less than from Paxton fine sandy loam. They concluded that when both air and moisture were ample, the texture of the soil did not have a marked effect on the growth and yield of potatoes.

Effect of manuring Sassafras silt loam. On Long Island, potatoes were grown in 1947 in a long continued field experiment dealing with the effect of annual manuring on vegetable crops, (Klute and Jacob, 10). Judging from the bulk density of the soil, the manuring increased its porosity, but the unmanured averaged more than 50 percent of total pore space. Although some of the manured soils averaged as high as 57 percent pore space, none of them gave significantly higher yields of potatoes than the well fertilized, unmanured treatments.

These results on Sassafras silt loam agree with the results from Wooster soil in that 50 percent of total pore space proved ample for potatoes. On the other hand, they differ, first, in that the Sassafras silt loam cropped annually had 50 percent of total pore space, and second, in that manuring increased it. In line with these indications that Sassafras silt loam is naturally more porous than Wooster, it may be added that it is one of the prominent potato soils of Long Island and New Jersey.

PRACTICAL CONCLUSIONS

The obvious general conclusion from the experience and experiment reported here is that insufficient porosity in Wooster and Canfield silt loams has been a factor limiting the yield of potatoes. From a broad viewpoint the chief significance of the work may lie simply in bringing to light this sensitivity of the potato plant to the physical condition of its soil.

On the other hand, four specific practical deductions and inferences may be enumerated:

1. The value of land for potatoes cannot be reliably judged by its productivity of other field crops. Better appraisal can be made by judging whether the soil will sift through a digger web instead of carrying over as large clods, or by determining whether it will withstand water-logging without settling and slaking (as shown in Figure 9).

2. Liberal application of manure, or plowing down of large green-manure crops, cannot be advocated as a means of developing suitable tilth for potatoes in soil of this character.

3. Old sods, or newly cleared land, are likely to be in good tilth for potatoes. The length of time that soils need to be left in sod to rebuild suitable tilth, however, remains undetermined. Very meager data at hand indicate that something more than six years and less than sixteen years are required in Wooster silt loam. There is the possibility that land might be left in sod specifically to recuperate, but no such recommendation is justified at this time.

4. Soils better suited to potatoes would possess a more permanent granular structure, or would be of coarser texture, than the silt loams studied here.

Texture of Prominent Potato Soils

In agreement with the above deduction, the soils on which potatoes are a nationally prominent crop are characteristically of lighter texture than the silt loam of the experiments reported here. The districts of large and intensive production are widely scattered, and the soils of most areas have been surveyed and rated for their productivity of potatoes. Based on these surveys, a list of the nationally prominent potato soils was compiled in 1938 by Morgan, Gourley and Ableiter (13). Of their list, all but two were of lighter texture than silt loam. Of the two silt loams, one was of the Portneuf soil of Idaho, shown in a soil survey (20) to have more sand and less fine silt than the Wooster silt loam shown in Table 15. As a whole, the mineral soils prominently used for potatoes range from light textured silt loams, through loams, to sandy loams. Well drained muck soils are also included.

That potatoes in Ohio should be grown on relatively light-textured soils was first advocated by Tussing in 1935 who presented a list of soils deemed suitable (18). Based largely on growers' experience, this list has been revised from time to time. Currently (12), it includes several silt loams, but no soil of heavier texture.

No attempt has been made in the Ohio listings to rate the relative productivity of the soils named. As an illustration of differences due to texture, the average yields from variety trials of 1932-35 are listed in Table 20, together with some recent data obtained since DDT has been used in the spray formulations. Growers' experience appears to be in line with these results. For example, at the last census three Ohio counties reported yields exceeding 300 bushels of potatoes per acre. In Huron and Ashland counties the commercial acreage was on muck; in Champaign county on Fox fine sandy loam.

As a whole, the evidence at hand shows that potatoes are being grown most successfully on light-textured soils which would be expected to be naturally well aerated.

TABLE 20.—Yield of Potatoes on Soils of Different Type in Ohio

Average of high-yielding varieties in trials of 1932-35, and of Irish Cobbler sprayed with formulations containing DDT in experiments of 1944-46.*

Soil and location	Average total per acre, bu.	
	1932-35	1944-46
Muck, Hardin County	409	541
Chenango fine sandy loam, Washington County	318	434
Wooster silt loam, Wayne County	238	286
Mahoning silty clay loam, Cuyahoga County	176	

*Data of 1944-46 supplied by J. P. Sleesman and J. D. Wilson.

Deterioration of Soil Structure as a Factor in the Decrease of Potato Acreage in Ohio

During the pioneer era in Ohio, potatoes were widely grown as an incidental cash crop and became known as crop that did best on "new land" (15). To judge from census reports, the era of land clearing ended by 1899, when more "improved land" was reported than at any census year before or since. Ten years later potatoes reached a peak of 212,000 acres. During these years the yield per acre was low but the trend was upward until about 1906; then it turned downward. After 1910, there was wide abandonment of acreage. By 1925 the land in potatoes was less than half what it had been (Fig. 10).

At the time, the declining yields and decrease of acreage were attributed to the prevalence of diseases. Wide experience in the state thus seems to have followed a pattern similar to that at the Experiment Station, related in the introduction. Though it was not understood at the time, deterioration of structure of virgin soil during the first decade of cropping and the corresponding decrease in its porosity, may well have been a prominent factor in the decrease of potato acreage, when virgin soil was no longer readily available.

About 1925, certified seed potatoes and fairly good sprayers became generally available, and interest in growing potatoes revived. With the adoption of disease control measures there was some improvement in yield, but the state average remained below 100 bushels per acre, and many growers reported that their returns failed to cover the increased cost of production. It was during the decade of 1925-35 that the question was pointedly raised as to why better crops were not being obtained. As neither growers' experience nor experiments gave an

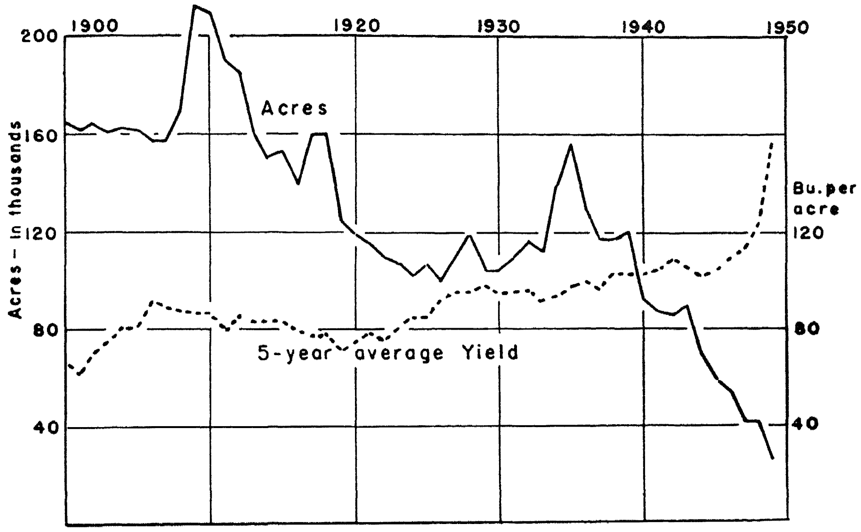

Fig. 10.—Potato acreage and trend of yield in Ohio since 1900. Data from Agricultural Statistics, 1949, and census of 1950.

answer applicable to silt loam and heavier soil, a second period of decline in acreage began after 1936 which has continued to the present.

In view of the good yields obtained on muck and on sandy loam, the question might be raised as to why an expansion of potato production on such soils has not balanced the decrease on other soils. Actually there has been some increase on muck, loam, and sandy loam, but the area of such soils in Ohio is relatively small, and they are in demand for other intensive crops.

SUMMARY

A fertilizer experiment started in 1894 with potatoes grown in rotation with wheat and clover was located partly on virgin Wooster silt loam and partly on previously cropped land. For the first 12 years the potato yields on the virgin soil were considerably higher than on the long cropped land, but after that declined. In contrast, the wheat and clover yields were well maintained.

At the time, the poor growth and yield of the potatoes was attributed to diseases surviving in the soil. The plants started well, but died down unevenly and prematurely, with some vascular darkening in the stems and tubers.

In crop-rotation experiments started in 1915 on previously cropped silt loam, potatoes, as before, grew poorly, with little or no benefit from the use of long rotations. Here again, the yield of other crops was good.

Planting certified seed and spraying the tops resulted in some improvement in yield after 1922, but the premature dying persisted, and yields of potatoes were mostly below 200 bushels per acre. By 1929 the plant pathologist studying the problem reached the opinion that the poor growth was not primarily due to pathogens.

The work reported here aimed to determine the soil condition underlying the poor growth and to find practical measures for correcting it.

Application of some of the minor nutrient elements to plots in the long continued fertilizer experiment resulted in no appreciable benefit.

In pot studies, the soil was observed to slake and settle when overwatered; thereafter, growth of potato stems soon terminated and the leaves gradually died. This settling and compaction occurred in long-cropped silt loam, but not in virgin soil from a forested block.

In the field, similar compaction was found after heavy rain, except that the plowed soil was not uniformly compacted throughout. Potato roots were most abundant in the looser portions, and often there were none at all in the most compact portions. The compaction presumably reduced the aeration of the roots and thus restricted growth.

Ventilating soil in the field by means of shallow tile lines laid directly under potato rows increased the yield of tubers an average of 24 percent.

Plowing down large green-manure crops alternate years over a period of 16 years failed to give a tilth favorable for potatoes. Similarly, application of 24 tons of shed manure per acre for nine consecutive years where early potatoes were grown failed to raise the average yield above 200 bushels per acre.

Determination of the average total pore space in the soil prior to harvest of the last seven crops of potatoes in the green-manure experiment gave no indication that total porosity was being increased by the incorporation of the organic matter. Likewise, the annual application of 24 tons of manure per acre did not appreciably increase the soil porosity above that of adjoining unmanured plots. Both manuring experiments ended with pore space averaging 48.5 percent of the total volume of the soil.

Clods devoid of living roots were found to have 47 percent or less of total pore space. From determinations of the water-retaining capacity of Wooster silt loam it is calculated that such clods in contact with free water would fill with water to the point where 1 percent or less of pore space remained for air. With 48.5 percent of pore space, as found in the manuring experiments, soil similarly wetted would be expected to have only four percent for air. Calculated air space at two lower levels of moisture are given.

Soil with higher proportion of pore space was found under sods of long standing as well as in a wooded tract. A 16-year sod, plowed for potatoes, retained 49 percent or more of pore space for five successive years and throughout these years gave yields exceeding 400 bushels per acre. In the sixth year the pore space averaged 48.6 percent and the yield dropped to 246 bushels. This experience followed a pattern similar to that obtained on virgin soil at the outset of the fertilizer experiment, although yields of 400 bushels per acre were not attained in those early years In another instance, after a six-year sod, yields exceeding 300 bushels per acre were obtained for two years while the pore space remained above 49 percent.

A few determinations of water-stable aggregation in the experimental plots of 1947 showed less than five percent of aggregates retained on 0.25-millimeter sieve in long cropped soil. Under old sods 20 percent or more were present.

The general conclusion is that insufficient porosity is a principal factor limiting the yield of potatoes on Wooster silt loam, and no practical procedure has been found for maintaining it in highly productive tilth. In technical terms, it needs to have at least 49 percent of total pore space to be in good condition for potatoes.

It is pointed out that the nationally prominent potato soils are of lighter texture than the silt loams used here. In Ohio, higher yields have been obtained from experiments on muck and on fine sandy loam than on silt loam.

The suggestion is advanced that Ohio's prominence as a potato producing state during the era of land clearing was due to the adequate porosity of virgin soil, and thereafter as porosity decreased potatoes were replaced by less sensitive crops.

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